

SAURON's Challenge for the Major Merger Scenario of Elliptical Galaxy Formation

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ABSTRACT

The intrinsic anisotropy δ and flattening ϵ of simulated merger remnants is compared with elliptical galaxies that have been observed by the SAURON collaboration, and that were analysed using axisymmetric Schwarzschild models. Collisionless binary mergers of stellar disks and disk mergers with an additional isothermal gas component, neglecting star formation cannot reproduce the observed trend $\delta = 0.55\epsilon$ (SAURON relationship). An excellent fit of the SAURON relationship for flattened ellipticals with $\epsilon \geq 0.25$ is however found for merger simulations of disks with gas fractions $\geq 20\%$, including star formation and stellar energy feedback. Massive black hole feedback does not strongly affect this result. Subsequent dry merging of merger remnants however does not generate the slowly-rotating SAURON ellipticals which are characterized by low ellipticities $\epsilon < 0.25$ and low anisotropies. This indicates that at least some ellipticals on the red galaxy sequence did not form by binary mergers of disks or early-type galaxies. We show that stellar spheroids resulting from multiple, hierarchical mergers of star-bursting subunits in a cosmological context are in excellent agreement with the low ellipticities and anisotropies of the slowly rotating SAURON ellipticals and their observed trend of δ with ϵ . The numerical simulations indicate that the SAURON relation might be a result of strong violent relaxation and phase mixing of multiple, kinematically cold stellar subunits with the angular momentum of the system determining its location on the relation.

Subject headings: methods: N-body simulations – galaxies: elliptical and lenticular – galaxies: evolution – galaxies: formation – galaxies: kinematics and dynamics – galaxies: structure

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1. Introduction

A popular formation scenario for early-type galaxies is the collision and merger of two roughly equal-mass galaxies with mass ratios between 1:1 and 4:1. This famous major merger scenario (Toomre & Toomre 1972) has been very successful in explaining observed properties of ellipticals, like their kinematics, surface density profile or isophotal shape (Gerhard 1981; Negroponte & White 1983; Barnes 1988, 1990; Barnes & Hernquist 1992; Hernquist 1992, 1993; Burkert 1993; Naab et al. 1999; Cretton et al. 2001; Naab & Burkert 2003; González-García & Balcells 2005; Jesseit et al. 2005; Bournaud et al. 2005; Naab & Trujillo 2006; Naab et al. 2006a; Robertson et al. 2006; Cox et al. 2006). Numerical simulations for example showed that the family of disk, fast rotating ellipticals could result from stellar disk galaxy mergers with unequal mass ratios of 3:1 to 4:1 (Barnes 1998; Bekki 1998; Naab et al. 1999; Naab & Burkert 2003; Bournaud et al. 2005; Naab et al. 2006a) or from gas-rich 1:1 to 2:1 disk mergers where the gas subsequently settles into the equatorial plane of the merger remnant and produces a new stellar disk component (Khochfar & Burkert 2005; Barnes & Hernquist 1996; Naab & Burkert 2001; Barnes 2002; Springel & Hernquist 2005). Boxy, slowly rotating ellipticals, on the other hand form in stellar disk-disk mergers with mass ratios of 1:1 to 2:1 (Heyl et al. 1994; Naab & Burkert 2003) or from multiple major disk mergers (Weil & Hernquist 1996). Bournaud et al. (2007) showed that repeated minor mergers result in remnant properties very similar to one corresponding to major mergers.

A serious problem of the major merger scenario was the fact that cosmological models do not predict a dependence of the mass ratio of mergers on total galaxy mass or luminosity (Khochfar & Burkert 2003). If, on the other hand, the mass ratio determines the isophotal shape and rotational properties of merger remnants one would expect that the ratio of the number of fast rotating, disk ellipticals to the number of slowly rotating, boxy systems should be independent of luminosity (Naab et al. 2006b). This is in contrast with observations that show a strong dependence of isophotal shape and rotational properties on galaxy mass. While massive galaxies are preferentially boxy, slow rotators, lower-mass ellipticals are predominantly disk and fast rotators (for a summary see Kormendy & Bender 1996). Khochfar & Burkert (2003) argued that this mass dependence of galaxy properties could be explained as a result of differences in the morphologies of the merging progenitors (see e.g. Kang et al. 2007). Using semi-analytical models they showed that gas-rich disk-disk mergers dominate at the low-mass end of ellipticals while intermediate mass ellipticals should have formed preferentially from mixed mergers involving a disk and an elliptical galaxy. Finally, the most massive early-type galaxies should have experienced a last elliptical-elliptical merger (dry merger) (Naab et al. 2006b). Mixed mergers have not yet been studied in details, although, according to Khochfar & Burkert (2003) they should be more frequent than dry mergers (see however Hopkins et al. 2007b). Dry mergers and their implications

for the formation of the red galaxy sequence have however received a lot of attention recently (Khochfar & Burkert 2005; González-García & van Albada 2005; Faber et al. 2005; Naab et al. 2006b; Boylan-Kolchin et al. 2006).

Further refinement of theoretical models has recently been achieved by including black-hole physics in simulations of galaxy mergers and elliptical galaxy evolution. Energetic feedback from central black holes might solve some pending problems of major merger models, like the suppression of late inflow of cold gas and star formation that would make ellipticals look much bluer than observed (Springel et al. 2005).

In summary, despite several still unsolved questions (e.g. Naab & Ostriker 2007), the major merger scenario has become a popular model in order to explain the origin of bulge-dominated, spheroidal galaxies (see e.g. Hopkins et al. 2007a,b).

Progress in understanding galactic evolution is often driven by strong interactions between observers and theorists. Increasingly more sophisticated theoretical/numerical models are confronted with continuously improving observations that lead to new theoretical challenges. One example is the SAURON project (Emsellem et al. 2004) which aims to determine the 2-dimensional structural and kinematical properties of early-type galaxies using a panoramic integral-field spectrograph. In order to interpret the observations and study the intrinsic galaxy structure, axisymmetric Schwarzschild models are applied to the observations (Cappellari et al. 2006, 2007). The results, published so far, have revealed interesting fine structures and physical properties which provide new and deeper insight into the origin of galaxies, in particular when compared to simulation (Bendo & Barnes 2000; Jesseit et al. 2007).

In this paper we confront a recently published SAURON analysis of preferentially axisymmetric elliptical galaxies (Cappellari et al. 2007) with the predictions of numerical merger simulations and cosmological models of galaxy formation. Section 2 summarizes the observations. Section 3 shows that simulations of collisionless and gaseous disk-disk mergers, neglecting star formation and stellar feedback cannot reproduce the observational results. We demonstrate that star formation and stellar energy feedback has a strong effect on the final structure of merger remnants, leading to a good agreement with the SAURON observations of fast rotating ellipticals. The origin of the round, almost isotropic, slowly rotating SAURON ellipticals is explored in section 4. Isolated, dry mergers of ellipticals that formed as discussed in section 3 cannot explain these objects. We show however that cosmological initial conditions, leading to a series of multiple major and minor mergers, coupled with local star bursts generate spheroidal stellar systems in very good agreement with the observations. Conclusions follow in section 5.

2. SAURON results

Cappellari et al. (2007) analyzed a subsample of 24 elliptical and lenticular galaxies of the SAURON survey which were biased against triaxiality and consistent with being axisymmetric stellar systems. Axisymmetric three-integral Schwarzschild models (Schwarzschild 1979; Cappellari et al. 2005) were used to determine the distribution of stellar orbits. For an investigation of the validity and accuracy of axisymmetric Schwarzschild models in reproducing the intrinsic properties of simulated merger remnants, see Thomas et al. (2007). As SAURON integral-field kinematics was only taken within the effective radius, the Schwarzschild calculations were restricted to a determination of the orbital parameters for the 50% most bound stars in each galaxy. From this, global galactic parameters were derived. The authors found two classes of spheroid-dominated galaxies, one with and one without significant amount of specific angular momentum (Emsellem et al. 2007). They called these groups slow and fast rotators, respectively. Following Binney (1978), for each galaxy the anisotropy parameter

$$\delta \equiv \frac{\Pi_{xx} - \Pi_{zz}}{\Pi_{xx}}. \quad (1)$$

was determined. Here, the z axis coincides with the symmetry and rotation axis of the axisymmetric galaxy,

$$\Pi_{ii} = \int \rho \sigma_i^2 d^3x \quad (2)$$

is the diagonal element of the velocity dispersion tensor in the i -th direction (Binney & Tremaine 1987), $\sigma_i^2 = \langle v_i^2 \rangle - \langle v_i \rangle^2$ is the local mean velocity dispersion in the i -th direction and ρ is the local stellar density. For axisymmetric systems $\Pi_{xx} = \Pi_{yy}$. In addition, the so called intrinsic ellipticity ϵ_{int} was determined as the edge-on ellipticity of the projected early-type galaxy, corrected for inclination effects.

The red and cyan filled circles in Fig. 1 show δ versus ϵ_{int} of the slow and fast rotating ellipticals of the SAURON sample, respectively. The population of slow rotators is intrinsically quite round ($\epsilon_{int} \leq 0.25$) and characterized by an almost isotropic velocity dispersion with $\delta \leq 0.15$. In contrast, the fast rotators are in general much flatter ($\epsilon_{int} \geq 0.3$) and more anisotropic with $\delta \geq 0.15$. This result is in conflict with the standard paradigm that fast rotating ellipticals are nearly isotropic systems while slowly rotating ellipticals are strongly anisotropic (Binney 1978). Burkert & Naab (2005) showed that projection effects play an important role for fast rotators and that even strongly anisotropic stellar systems

would appear isotropic when viewed under random projection. The origin of the isotropic, slowly rotating population is however puzzling. Despite the fact that the analyzed SAURON sample is still small, Fig. 1 clearly reveals a strong correlation between δ and ϵ_{int} which can be fitted by the empirical relationship (solid line)

$$\delta = (0.55 \pm 0.1)\epsilon_{int}. \quad (3)$$

Ellipticals are usually analysed, using the classical (V/σ) - ϵ anisotropy diagram (Binney 1978, 2005) with V and σ being the maximum projected rotational velocity and projected central velocity dispersion, respectively, and ϵ the apparent projected ellipticity. Binney (2005) demonstrated that for axisymmetric systems, seen edge-on, the anisotropy is given by

$$\delta = 1 - \frac{1 + (V/\sigma)^2}{q(e)[1 - \alpha(V/\sigma)^2]} \quad (4)$$

where α measures the shear in the stellar streaming velocity and

$$q(e) \equiv \frac{0.5}{1 - e^2} \times \frac{\arcsin e - e\sqrt{1 - e^2}}{\frac{e}{\sqrt{1 - e^2}} - \arcsin e} \quad (5)$$

with $e = (1 - (1 - \epsilon)^2)^{1/2}$. α is in general small. The dashed curves in Fig. 1 show the expected correlation between δ and ϵ for different values of V/σ , adopting $\alpha = 0.15$ (Cappellari et al. 07). Due to the effect of rotational flattening, ϵ increases with increasing V/σ for a given value of δ . The fast rotating SAURON ellipticals (cyan circles) cluster around $V/\sigma \approx 0.5$ while the slowly rotating sample (red circles) is characterized by $V/\sigma \leq 0.25$.

Open circles in Fig. 1 correspond to objects classified as S0 galaxies. Two of these objects have properties that are similar to fast rotating ellipticals, indicating either a similar origin or classification problems. Note however the 3 highly elliptical and fast rotating outliers that indicate that S0s are at least sometimes more rotationally dominated than fast rotating early-type galaxies.

In the next sections we will explore the question whether these observational results are in agreement with the major merger scenario of early-type galaxy formation.

3. The Origin of the Fast Rotating SAURON Ellipticals

We start with an analysis of a large sample of collisionless merger remnants of disk galaxies with different mass ratios and initial orientations. The progenitors consisted of a stellar disk, a stellar bulge and a surrounding dark matter halo. Gas and star formation has been neglected. Details of the initial conditions, the simulations and the properties of the merger remnants have been presented elsewhere (Burkert & Naab 2003; Naab & Burkert 2003; Khochfar & Burkert 2006; Naab et al. 2006a). There it was shown that equal-mass mergers with progenitor mass ratios of 1:1 to 2:1 produce slowly rotating and often boxy remnants, resembling massive ellipticals, while unequal-mass mergers with mass ratios of 3:1 - 4:1 generate fast rotating, disk-like remnants, resembling lower-mass ellipticals.

In order to match the SAURON analysis, δ was determined from the 50% most bound stellar particles of the relaxed merger remnants and ϵ_{int} from the edge-on projected stellar distribution. Cappellari et al. (2007) used axisymmetric models where $\Pi_{xx} = \Pi_{yy}$. One should however note that especially 1:1 mergers are quite triaxial. Our 1:1 mergers have a roughly homogeneous distribution of the ratio Π_{yy}/Π_{xx} which lies in the range of $\Pi_{yy}/\Pi_{xx} = 0.75 - 1$. We therefore use an averaged value of the velocity dispersion in the equatorial plane in order to determine the anisotropy:

$$\delta \equiv \frac{0.5(\Pi_{xx} + \Pi_{yy}) - \Pi_{zz}}{0.5(\Pi_{xx} + \Pi_{yy})} \quad (6)$$

which in the axisymmetric case reduces to Eq. 1.

Fig. 2 shows the distribution of all collisionless merger remnants in the δ - ϵ_{int} -diagram. In agreement with previous work, 1:1 remnants (red triangles) are slowly rotating ($V/\sigma \leq 0.25$), consistent with the slow rotators found by the SAURON team. 2:1 - 4:1 merger remnants fall into the regime of $0.25 \leq V/\sigma \leq 0.75$, consistent with fast rotating SAURON ellipticals. However, in contrast to the SAURON observations, no correlation of δ with ϵ is visible. Independent of V/σ , ϵ or the progenitor mass ratio, collisionless merger remnants are characterized on average by an anisotropy of $\delta \approx 0.35$ with a large spread. This value is close to the anisotropy found for the most flattened, fast rotating SAURON ellipticals. The disagreement increases however for less flattened, slow rotators. On average, even the fast rotating SAURON ellipticals have substantially lower anisotropies and lower ellipticities than our 2:1 to 4:1 merger remnants.

The disagreement is largest for slowly rotating systems. Equal-mass (1:1) collisionless merger remnants, despite their slow rotation, cannot reproduce at all the observed properties of the slow rotators of the SAURON sample which are much less anisotropic and therefore

much less flattened than predicted by the numerical simulations.

One possible explanation for the disagreement between observations and the theoretical models could be that the SAURON collaboration focussed especially on axisymmetric systems, characterized by $\Pi_{yy}/\Pi_{xx} \approx 1$. We tested whether this could generate a bias towards preferentially spherical, low anisotropy systems by investigating the location of our axisymmetric merger remnants with $\Pi_{yy}/\Pi_{xx} \geq 0.9$ in Fig. 2. Their distribution turns out not to be different compared with the complete sample, ruling out such a solution.

Naab et al. (2006a) emphasised the importance of gaseous energy dissipation during galaxy mergers. They studied a set of disk mergers with mass ratios 1:1 and 3:1, including gas with a mass fraction of 10 per cent of the total disk mass. The gas dynamics was followed during the merging process, adopting an isothermal equation of state. Star formation and stellar feedback was neglected. Despite this simplification, Naab et al. (2006a) showed that a dissipative gas component, settling into the galactic center through its gravitational force has a strong effect on the orbital structure of the merger remnant, leading to asymmetries of the line-of-sight velocity distribution of rotating ellipticals that are in much better agreement with observations than collisionless merger remnants (see also González-García et al. 2006). The anisotropy and ellipticity of the 1:1 and 3:1 merger remnants with 10% gas however turns out to be very similar to the distribution of the collisionless merger sample. Clearly, a 10% gas fraction as expected in evolved disk galaxies does not solve the problem either.

Ellipticals are in general old systems that formed at a time when disk galaxies were still quite gas-rich. Star formation and stellar as well as central black hole feedback therefore is expected to have played an important role during galaxy mergers (Hopkins et al. 2007a,b). In order to investigate this question we have started a new series of gas-rich ($\geq 20\%$ gas) disk mergers, using GADGET2 and taking into account star formation as well as stellar and black hole feedback as described by Springel & Hernquist (2003) and Springel et al. (2005). A detailed analysis of these simulations will be presented in a subsequent paper (Johansson et al., in preparation). The triangles in Fig. 3 show how star formation and energetic feedback affects the anisotropy and ellipticity of the merger remnants. Large triangles correspond to simulations, including black hole accretion, merging and black hole feedback. Five simulations have been repeated without taking into account black holes. They are represented in Fig. 3 by the smaller triangles. For a more detailed investigation of how star formation, energetic feedback and black hole physics affects the final structure of the merger remnants, table 1 compares the anisotropies and ellipticities of the collisionless merger simulations (columns 2 and 3) with those, starting with the same initial geometries and mass ratios, however now including 20% of gas, star formation as well as stellar and black hole feedback (columns 4 and 5). The columns 6 and 7 finally show the results for the simulations

where black hole accretion and feedback has been neglected. The initial conditions are shown in the first column of table 1 and are defined in table 1 of Naab & Burkert (2003).

Fig. 3 and table 1 show, that star formation and stellar energetic feedback has a strong effect on the anisotropy and ellipticity of merger remnants. We still find a trend of decreasing rotational support, i.e. decreasing V/σ with decreasing mass ratio of the progenitor disks. In addition, now, the scatter in the δ versus ϵ_{int} diagram is much smaller and a clear correlation between δ and ϵ_{int} is visible that can be fitted by a linear relationship (dotted line)

$$\delta = 0.67\epsilon_{int}, \quad (7)$$

which is somewhat steeper than the SAURON relation (solid line).

It is interesting that including star formation, the location of the merger remnants in the δ - ϵ_{int} diagram shifts closer to the dotted line, independent of whether they were above this correlation or below it in the collisionless merger case. For example, while the 3:1 merger with initial geometry 10 in the collisionless case formed a remnant that is characterized by $(\epsilon_{int}/\delta) = (0.51/0.14)$, including star formation and black hole physics moves this system up to values of $(\epsilon_{int}/\delta) = (0.55/0.33)$. Neglecting black holes, the values are very similar with $(\epsilon_{int}/\delta) = (0.55/0.35)$. An other example is the 1:1 merger with geometry 13 that in the collisionless case is located at $(\epsilon_{int}/\delta) = (0.44/0.38)$ and that with star formation shifts down to $(\epsilon_{int}/\delta) = (0.27/0.24)$, much closer to the dotted line than previously. In general, star formation is the dominant process. As shown by the small triangles in Fig. 3 and table 1, the effect of black hole accretion and feedback on the structure of the merger remnants is small.

The influence of the initial gas ratio on the results is indicated by the cyan triangles which show the results of three 3:1 mergers of two co-planar disk galaxies with initial gas baryon fractions of 20%, 40% and 80%. With increasing gas fraction the remnants move along the dotted curve towards smaller ellipticities and anisotropies.

4. The Origin of Slowly Rotating, Isotropic, Massive SAURON Ellipticals

The merger simulations of disk galaxies with star formation still cannot explain the almost round and isotropic SAURON ellipticals with $\epsilon \leq 0.2$ and $\delta \leq 0.15$. Mergers between ellipticals (dry mergers) have been suggested to dominate these slowly rotating, red galaxies (Khochfar & Burkert 2003; Faber et al. 2005; Naab et al. 2006b). A strong motivation for the dry merger scenario is the fact that old, red ellipticals have masses that are much larger

than typical spiral galaxies which basically rules out the possibility that they could have formed by a binary spiral-spiral merger (Naab & Ostriker 2007).

We investigated the dry merger scenario by re-merging the Gadget disk-disk merger remnants, discussed in the previous paragraph. The results of five 1:1 early-type mergers are shown by the filled black points in Fig. 3. Although the explored parameter space is still very small it is already obvious from the location of the black points that early-type mergers in general are unlikely to explain the slowly rotating, isotropic SAURON ellipticals. The data points cluster around $\epsilon_{int} \approx 0.57$ and $\delta \approx 0.43$ which is close to the relationship between anisotropy and ellipticity (dotted line) found for disk-disk mergers with star formation. From a dynamical point of view, these dry merger remnants are similar to gas-rich disk mergers with star formation. Naab et al. (2006b) had analysed the structure of ellipticals, formed through dry re-merging of ellipticals that were generated from collisionless, 1:1 and 3:1 stellar disk mergers as discussed in section 3. Note that, as shown in Fig. 2, the progenitor ellipticals do not lie on the SAURON relation. Nevertheless, it is interesting that re-merging of these systems places them nicely on the δ - ϵ_{int} relation described by Eq. 7 (open circles in Fig. 3). Still, these merger remnants are faster rotating, more anisotropic and more ellipsoidal than the slowly rotating SAURON ellipticals.

Yet another possibility to generate spheroidal ellipticals are multiple mergers in cosmological high-density regions. Naab et al. (2007) investigated the formation of a number of massive galaxies using high-resolution cosmological simulations in a Λ CDM universe. The calculations were simple, including only photoionization and cooling of the interstellar medium as well as star formation. AGN and supernova feedback was neglected. In these simulations efficient cooling of gas generated rapid gas infall into smaller dark halo density perturbations, followed by a burst of star formation. At the same time, these substructures merged into massive spheroidal stellar galaxy, resembling a present-day, red giant elliptical. Shock heating in the later phases generated a surrounding hot gaseous halos that suppressed late star formation, leading at the end to a red, old galaxy (Birnbom & Dekel 2003; Birnbom et al. 2007).

The green points in Fig. 3 show the location of three spheroidal galaxies presented in Naab et al. (2007) and 7 additional galaxies of similar mass simulated in the same manner. The distribution is in excellent agreement with the SAURON observations of red, massive ellipticals. Interestingly, the simulations reproduce not only the observed low ellipticities and anisotropies. They also show the same trend of anisotropy with ellipticity as observed.

5. Summary and Discussion

The numerical simulations, discussed in the previous sections, have shown that interstellar gas dynamics, star formation and stellar feedback plays a crucial role in order to reproduce the observed kinematical and isophotal properties of fast rotating, early-type galaxies. The final structure of the merger remnants depends on the initial mass ratio and gas fraction. The remnants are more round, less anisotropic and more rotationally supported the smaller the mass ratio $M_1/M_2 \geq 1$ of the progenitors and the larger the initial gas fraction. The dependence of δ on ϵ_{int} is in agreement with the observed trend found in the SAURON sample.

Subsequent dry re-merging of disk-disk merger remnants however does not generate the observed slowly-rotating red SAURON ellipticals with small anisotropies and ellipticities. This indicates that at least some early-type galaxies on the red galaxy sequence formed in a different way. We find that multiple mergers of stellar substructures that formed from cold gas infall into dark matter halos in cosmological simulations produce round, isotropic and slowly-rotating relaxed stellar systems that are in perfect agreement with the SAURON observations. Multiple mergers of stellar systems in dense group environments therefore appear to be a promising alternative scenario for the origin of the red, massive galaxy population.

Despite the fact that merger simulations with star formation lead to a correlation between anisotropy and ellipticity ($\delta = 0.67 \times \epsilon_{int}$) that is very similar to that inferred from observations its origin is not understood yet. It is interesting that merger remnants appear to move closer towards this relation along lines of constant V/σ (i.e. roughly constant specific angular momentum) in the case of a strong relaxation process. Here, strong relaxation is defined as the merger of a system of kinematically cold systems of stars that later on break up and generate a kinematically hot stellar remnant. Several conditions could lead to such a violent dynamical process. The cold stellar clumps could for example have formed in the star-bursting tidal tails of interacting, gas-rich disk galaxies. Another possibility is the cosmological multiple merging of dark matter substructures with an embedded stellar systems. The SAURON relation might represent the relaxed and phase-mixed end state of these complex mergers with the location of the remnant on the relation being determined by its specific angular momentum which is related to its value of V/σ . More theoretical work will be required in order to better understand these interesting questions and their connection to early-type galaxy formation.

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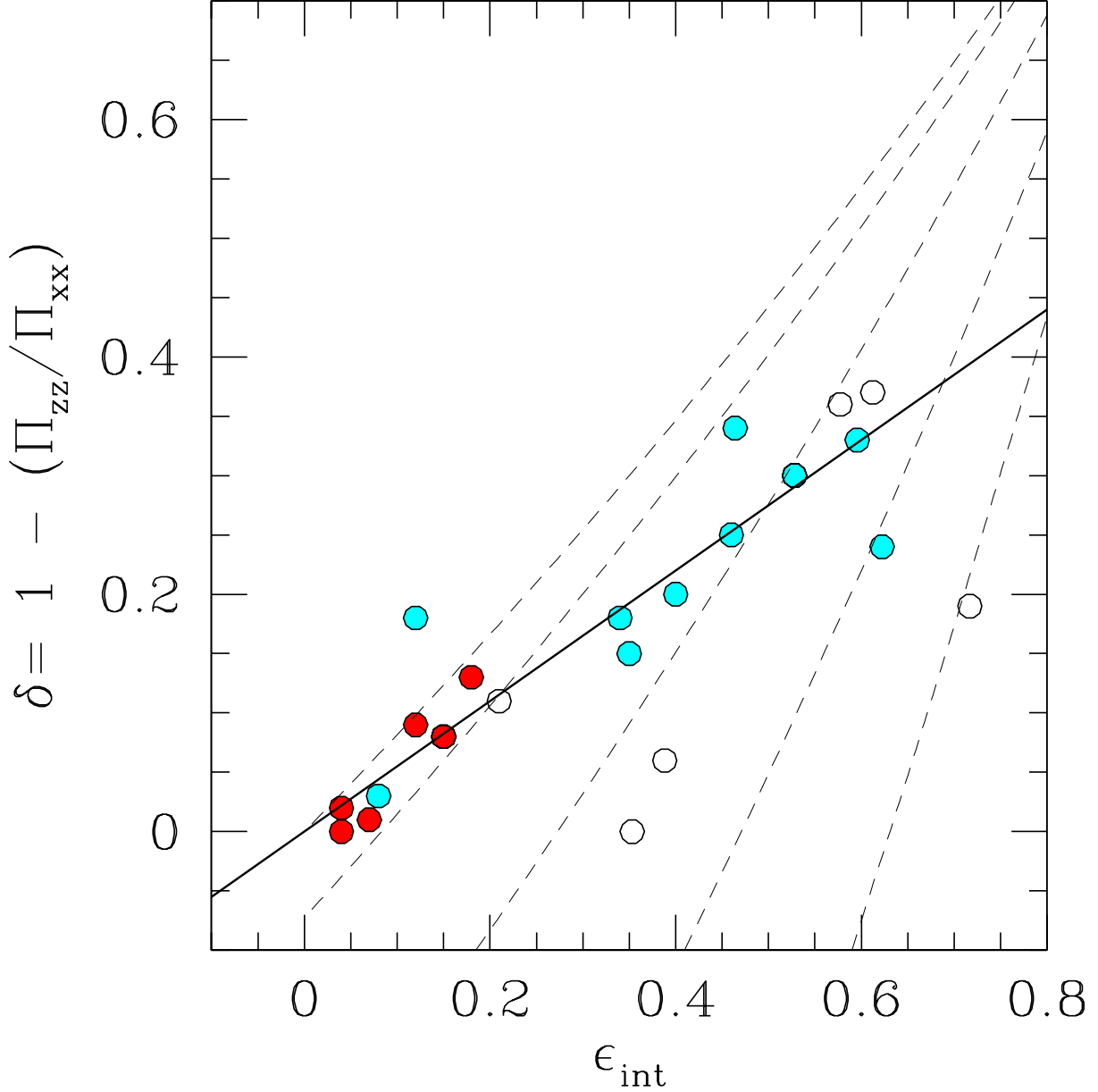


Fig. 1.— The anisotropy δ versus the edge-on projected ellipticity ϵ_{int} is shown for SAURON ellipticals. The effect of rotation on the ellipticity is demonstrated by the dashed lines which from left to right show the theoretically predicted correlation $\delta(\epsilon)$ (Eqs. 4 and 5) for constant values of $V/\sigma=0,0.25,0.5,0.75,1$, respectively. Red and cyan filled circles show slowly and fast rotating SAURON ellipticals, respectively. Open circles show objects, classified as S0 galaxies.

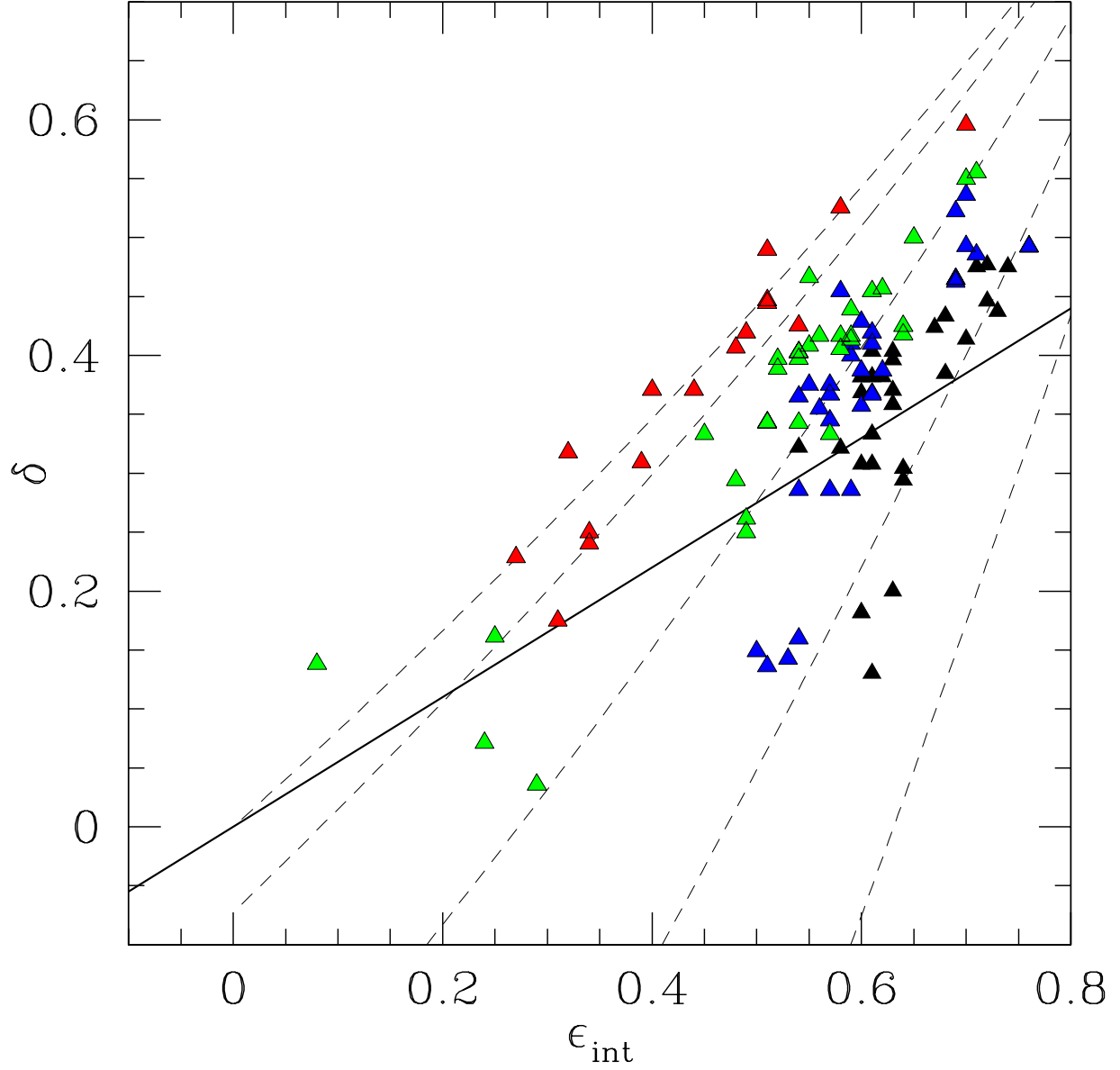


Fig. 2.— The structure of dissipationless merger remnants (triangles) is compared with the SAURON relation, represented by the solid line (dashed lines, see Fig. 1). The red, green, blue and black filled triangles correspond to dynamically relaxed merger remnants of collisionless stellar disk mergers with mass ratios 1:1, 2:1, 3:1 and 4:1, respectively.

Table 1: Anisotropy parameter and ellipticity of merger remnants

mass ratio/ geometry	ϵ_{int} stellar	δ stellar	ϵ_{int} SF+BH	δ SF+BH	ϵ_{int} SF	δ SF
1:1/7	0.49	0.41	0.36	0.20		
1:1/10	0.34	0.24	0.29	0.16	0.21	0.12
1:1/13	0.44	0.38	0.27	0.24	0.28	0.24
2:1/4	0.64	0.61	0.60	0.46		
2:1/10	0.24	0.07	0.47	0.37		
2:1/14	0.52	0.61	0.50	0.31		
3:1/4	0.69	0.47	0.63	0.44	0.56	0.39
3:1/10	0.51	0.14	0.55	0.33	0.55	0.35
3:1/14	0.59	0.42	0.61	0.24	0.62	0.25

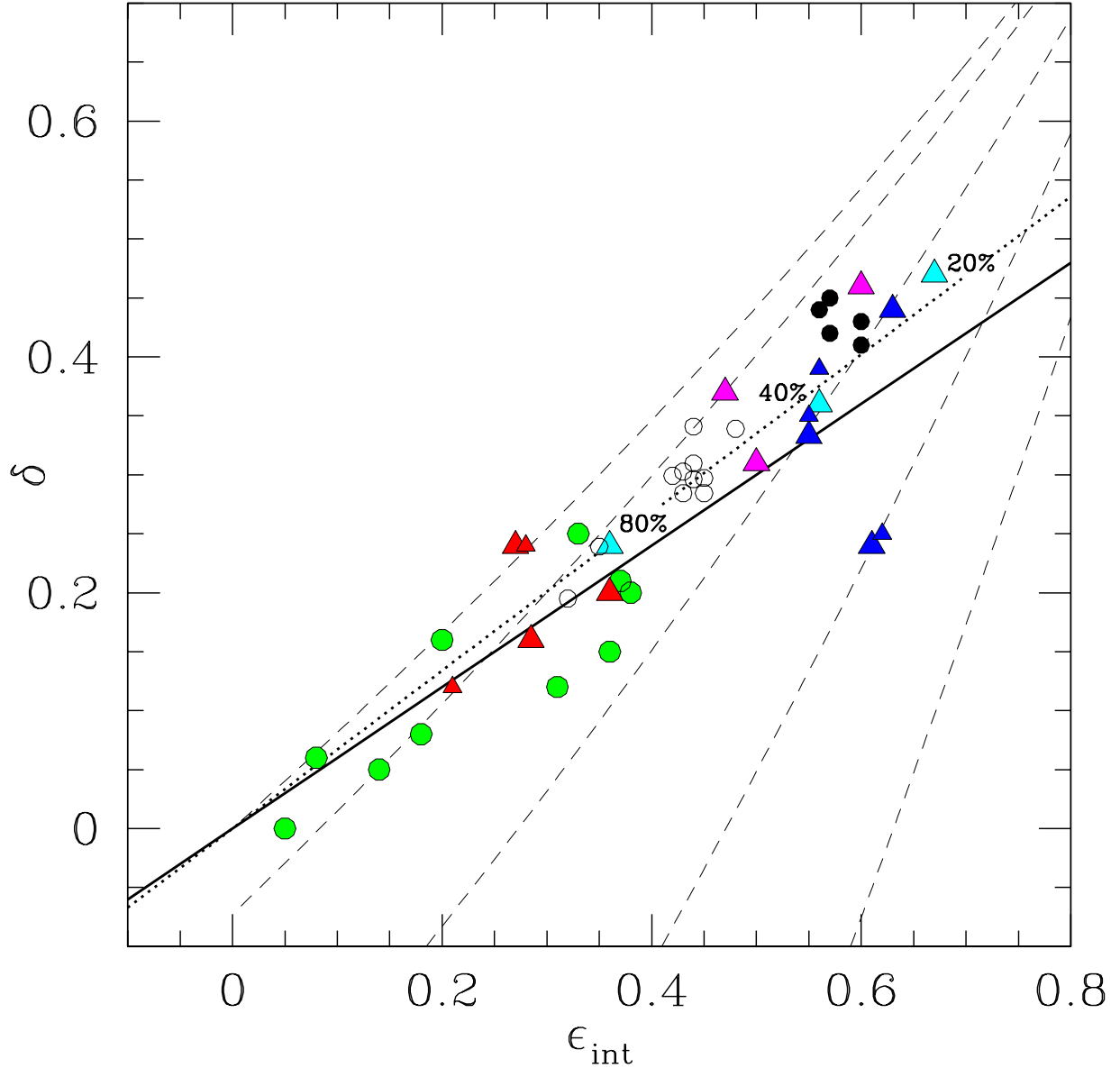


Fig. 3.— Same as Fig. 2. Here, red and blue large triangles show the location of 1:1 and 3:1 merger remnants with 20% gas, including star formation and black hole accretion as well as energetic feedback from stars and black holes. The smaller triangles show merger simulations without black hole physics (see also table 1). Cyan triangles show the results of a co-planar disk merger, including star formation, black hole physics and energetic feedback processes with initially 20%, 40% and 80% gas, respectively. All data points can be fitted well by a linear relationship of δ with ϵ_{int} that is shown by the dotted line. It is somewhat steeper than the SAURON relation (solid line). Green circles correspond to cosmological simulations of spheroidal galaxy formation that take into account star formation but neglect stellar feedback and black hole physics. Filled black circles show five dry equal-mass mergers of merger remnants that were produced from GADGET merger simulations of disks with 20% gas, taking into account star formation and black hole physics. Open circles show the results of 1:1 and 3:1 dry mergers of ellipticals that were generated by collisionless mergers